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Letter

The cosmic timeline implied by the highest redshift quasars

Fulvio Melia[1,2,a]

[1] Department of Physics, The Applied Math Program, The University of Arizona, Tucson, AZ 85721, USA
[2] Department of Astronomy, The University of Arizona, Tucson, AZ 85721, USA

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Abstract The conventional picture of supermassive black-hole growth in the standard model had already been seriously challenged by the emergence of $\sim 10^9\ M_\odot$ quasars at $z \sim 7.5$, conflicting with the predicted formation of structure in the early ΛCDM Universe. But the most recent *JWST* discovery of a $\sim 10^8\ M_\odot$ source at $z \sim 10.1$ argues even more strongly against the possibility that these black holes were created in Pop II or III supernovae, followed by Eddington-limited accretion. Attempts at resolving this anomaly have largely focused on the formation of seeds via an exotic, direct collapse of primordial gas to an initial mass $\sim 10^5\ M_\odot$ – a process that has never been seen anywhere in the cosmos. Our goal in this *Letter* is to demonstrate that the emergence of these black holes is instead fully consistent with standard astrophysics in the context of the alternative Friedmann–Lemaître–Robertson–Walker cosmology known as the $R_{\rm h} = ct$ universe. We show that, while the predicted evolution in the standard model is overly compressed, the creation, growth and appearance of such high-z quasars fall comfortably within the evolutionary history in this cosmology, thereby adding considerable observational support to the existing body of evidence favoring it over the standard scenario.

1 Introduction

The recent discovery [1] of an X-ray luminous supermassive black hole, UHZ-1, at a confirmed spectroscopic redshift $z = 10.073 \pm 002$ [2], emphasizes more than ever the time compression problem in the early ΛCDM Universe [3]. With an inferred mass of $M = 10^7 - 10^8\ M_\odot$, this object should have taken over ~ 700 Myr to grow via standard Eddington-limited accretion, starting with a supernova remnant mass of $\sim 10\ M_\odot$ (see Eq. 2 below). Yet it appears to us a mere ~ 300 Myr after Pop III stars started forming some ~ 200 Myr beyond the big bang. On the flip side, its host galaxy is estimated to have a stellar mass $M_* \sim 1.4^{+0.3}_{-0.4} \times 10^8\ M_\odot$ [2], so the ratio M_*/M is two to three orders of magnitude smaller than local values, consistent with a scenario in which the black hole formed first within the core of an isolated Pop III remnant [4–6], followed by the gradual aggregation of proto-galactic stars around it. The main problem therefore seems to be the timeline in ΛCDM.

2 Background

The growth of black-hole seeds (regardless of their mass) in conventional astrophysics is constrained by the maximum accretion rate allowed by the outward radiation pressure associated with the luminosity produced via the dissipation of gravitational energy [7]. When the ionized plasma is hydrogen-rich, this limit is known as the Eddington value, $L_{\rm Edd} \approx 1.3 \times 10^{38}(M/M_\odot)$ ergs s^{-1}. The unknown factor in this process is the efficiency, ϵ, with which rest-mass energy is converted into radiation, fixing the accretion rate, $\dot{M} = L_{\rm bol}/\epsilon c^2$, in terms of the actual bolometric luminosity $L_{\rm bol}$, which may be different from $L_{\rm Edd}$. Taking all possible variations of accretion-disk theory into account, one generally adopts a fiducial value $\epsilon = 0.1$ for this quantity [7].

Thus, if the accretion rate is Eddington-limited, one may combine these simple expressions to derive the black-hole growth rate,

$$\frac{dM}{dt} = \frac{1.3 \times 10^{38}\ \text{ergs/s}}{\epsilon c^2 M_\odot}\, M \tag{1}$$

John Woodruff Simpson Fellow.

[a] e-mail: fmelia@email.arizona.edu (corresponding author)

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[8,9]. Its straightforward solution is known as the Salpeter relation,

$$M(t) = M_{\rm seed} \exp\left(\frac{t - t_{\rm seed}}{45\ {\rm Myr}}\right), \quad (2)$$

where $M_{\rm seed}$ ($\sim 5 - 25\ M_\odot$) is the supernova-remnant seed mass created at time $t_{\rm seed}$.

What is particularly challenging to the standard model is that there is no evidence of UHZ-1 accreting at a greatly super-Eddington rate, which would be required to account for its anomalously rapid growth within such a short time [10,11]. This follows a well-defined pattern in which the inferred luminosity in other high-z supermassive black holes with reasonably estimated masses has thus far been at, or near, the Eddington value (see, e.g., Fig. 5 in [12]). Specifically for the bolometric luminosity of the other three quasars we shall be discussing in this *Letter*, J0313-1806 ($z = 7.642$) is accreting at $0.67 \pm 0.14\ L_{\rm Edd}$ [13], J1342+0928 ($z = 7.54$) at $1.5^{+0.5}_{-0.4}\ L_{\rm Edd}$ [14], and J1007+2115 ($z = 7.515$) at $1.06 \pm 0.2\ L_{\rm Edd}$ [15]. Quite alarmingly, all four of these sources, but particularly UHZ-1, would thus have had to start growing *before* the big bang, which is unrealistic [9,16].

Some attention has thus been given to the massive seed proposal [17,18], which would necessitate the birth of black holes with a mass $\sim 10^5\ M_\odot$ at $z \sim 30$, even before the formation of Pop II and III stars. But this scenario is even more difficult to confirm observationally. The catastrophic events creating such massive objects would likely be too brief for us to see them directly. Observationally, these 'intermediate-mass' black holes could be detected after they formed nearby, but the evidence is sparse and inconclusive. For example, the low-luminosity active galactic nucleus NGC 4395 at 4 Mpc may be harboring a $\sim 3.6 \times 10^5\ M_\odot$ black hole in its core [19]. Perhaps ultra-luminous X-ray sources in neighboring galaxies may be black holes with $M \sim 1,000\ M_\odot$ [20], though this is well below what is required. It is also possible that intermediate-mass black holes may have been discovered in globular clusters, but none has yet stood up to careful scrutiny [21]. The conclusion seems to be that the creation of massive seeds may be contemplated theoretically, but none has yet been found. And anyway, if some are discovered in dwarf active galactic nuclei, they may very well have simply grown to their observed intermediate mass via steady accretion rather than having been created by some exotic event.

3 Blackhole growth in $R_{\rm h} = ct$

In this *Letter*, we shall demonstrate that, in contrast to the major difficulties one faces in accounting for the 'too-early' appearance of supermassive black holes in the context of ΛCDM, all of the characteristics of these objects, including their mass and redshift, and our current understanding of how and when the first stars formed and then died as Pop III supernovae, are remarkably consistent with the time versus redshift relation in the $R_{\rm h} = ct$ cosmology (see Fig. 1). This issue has been addressed before with the growing number of quasars at redshifts $z \gtrsim 7$ [16,22,23]. In all these cases, the time compression problem faced by ΛCDM has been eliminated by the use of $R_{\rm h} = ct$ as the background cosmology.

But the most recent discovery of UHZ-1 even closer to the big bang has raised the tension considerably. Nevertheless, we shall show that all of these quasars – those at $z \gtrsim 7.5$ and this most recent addition to the earliest supermassive black-hole family – are self-consistently accounted for by the formation of supernova remnant seeds at $22 \lesssim z \lesssim 15$, and their subsequent Eddington-limited growth through the Epoch of Reionization (EoR) beginning at $z \sim 15$, to the redshift at which they were discovered.

The pivotal events believed to have occurred in the early Universe may be briefly described as follows, based on many detailed simulations carried out in recent years [24–35]. At least in the context of ΛCDM, with concordance parameters $\Omega_{\rm m} = 0.307$, $k = 0$, $w_\Lambda = -1$ and Hubble constant $H_0 = 67.7\ {\rm km\ s^{-1}\ Mpc^{-1}}$ [36], the Universe became transparent at $t \sim 0.4$ Myr, heralding the beginning of the so-called Dark Ages lasting until the first (Pop III) stars formed $\sim 200 - 300$ Myr later, at the core of mini halos with mass $\sim 10^6\ M_\odot$ [4–6].

There is still some debate about whether this delay of ~ 200 Myr between the big bang and the creation of the first stars could be circumvented somehow, to mitigate the time compression problem in ΛCDM, but it is difficult to see how the primordial gas could have cooled any faster. By comparison, this time corresponded to $z \sim 70$ in the $R_{\rm h} = ct$, as we shall see shortly via the use of Eq. (3).

A further delay of $\gtrsim 100$ Myr [37,38] would have ensued while the hot gas expelled by Pop III stars cooled and re-collapsed, facilitating the formation of Pop II stars. All told, the supernova remnant seeds growing into supermassive black holes could not have formed earlier than ~ 300 Myr after the big bang. Once these stars, and the black holes they subsequently spawned, started emitting UV radiation, the Universe initiated a transition to reioniozation, a process that observationally lasted over the redshift range $15 \lesssim z \lesssim 6$ [39,40]. In the standard model, the EoR therefore stretched over a cosmic time $400 \lesssim t \lesssim 900$ Myr, in significant tension with the timeline required for the supermassive black holes to grow to their observed mass.

These essential features of black-hole growth in ΛCDM are shown in Fig. 2, along with the corresponding evolutionary trajectories in this model of the four most distant quasars highlighted in Fig. 1. The discordance between the theoretical predictions and the observational constraints is quite evident in this case, showing that our current understanding of

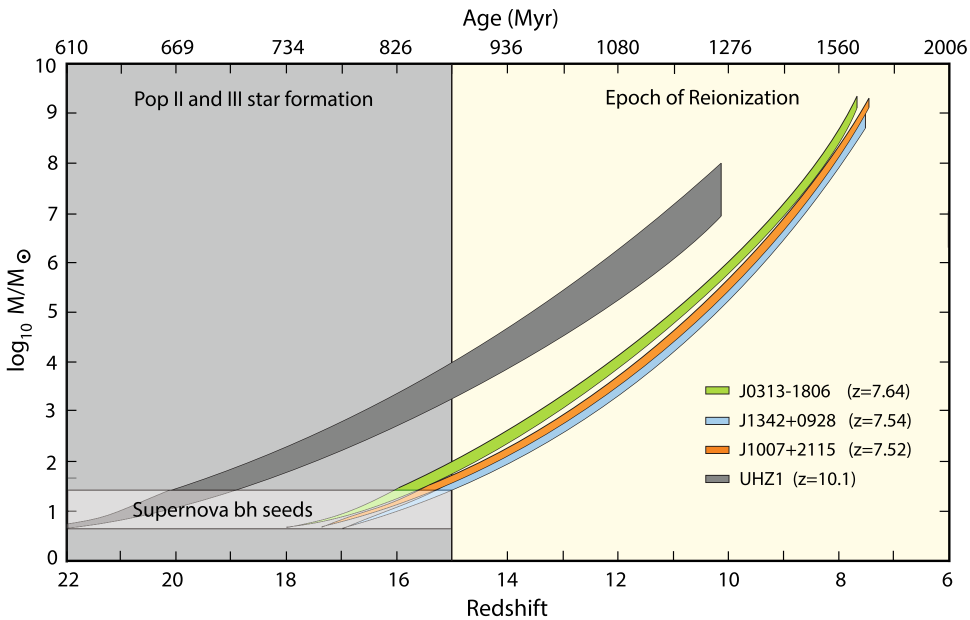

Fig. 1 Growth history in the $R_h = ct$ cosmology of the four most distant quasars discovered thus far. Pop II and III supernova seeds formed with initial masses $5\ M_\odot \lesssim M_{\rm init} \lesssim 25\ M_\odot$ at redshifts $22 \gtrsim z \gtrsim 15$, and grew via Eddington-limited accretion to a mass $M \sim 10^7 - 10^8\ M_\odot$ in one case, and $M \sim 10^9\ M_\odot$ by redshift ~ 7.5 for the other three. This seed formation corresponds very well with our understanding of how the earliest stars formed (and died), promoting the transition from the 'dark ages' to the Epoch of Reionization (EoR) at $z \sim 15$. The width of each swath indicates the possible range of M versus z given the unknown seed mass and the error in M at $z = 10.1$ and ~ 7.5. If the initial seed were $M_{\rm init} \sim 25\ M_\odot$, however, all four of these supermassive black holes would have begun their growth at $20 \lesssim z \lesssim 15$, just prior to the onset of the EoR

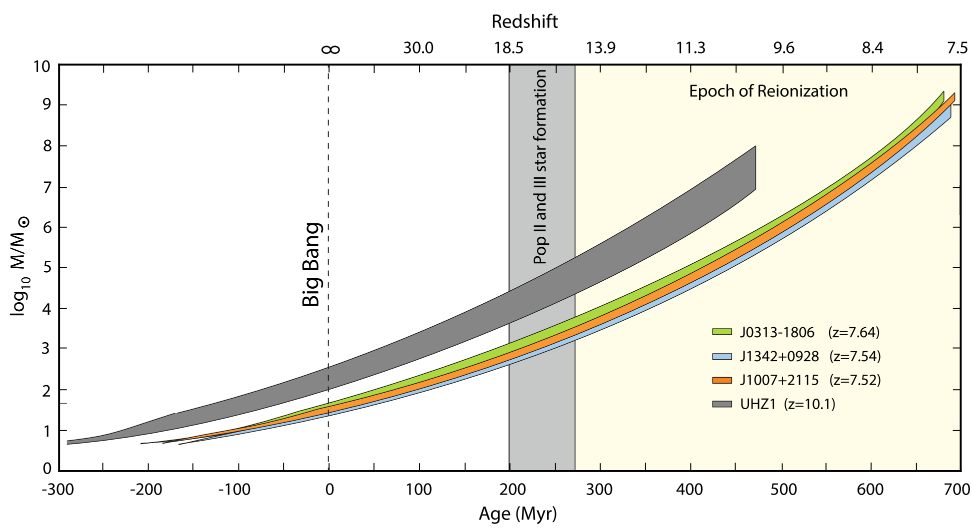

Fig. 2 Growth history of the four most distant quasars in *Planck*-ΛCDM. The seeds have the same mass as those in Fig. 1, but here their formation had to take place well before the Big Bang. In this case, the birth and growth of such supermassive black holes do not comport at all with our understanding of how the earliest stars formed (and died), and the transition from the 'dark ages' to the Epoch of Reionization (EoR) at $z \sim 15$

how structure formed in the early Universe is inconsistent with the appearance of such massive objects so quickly after the Big Bang. Indeed, if the seeds for these objects were $\sim 5 - 25\ M_\odot$ black holes, and if they subsequently grew at about the Eddington rate, they would have had to start well before the Big Bang itself, which is clearly unphysical.

In the $R_h = ct$ universe, however, the redshift-time relation is given by the expression

$$1 + z = \frac{t_0}{t}\ , \quad (3)$$

where $t_0 = H_0^{-1}$ is the age of the Universe today [3,41]. Thus, for the same Hubble constant H_0, the Dark Ages in this model ended at ~ 878 Myr, while the EoR extended from ~ 878 to ~ 2 Gyr (see Fig. 1). It is important to emphasize that the EoR redshift range is measured observationally, independently of the cosmology. What differs between the two models, however, is the mapping of redshift to age.

Thus, with $R_h = ct$ as the background cosmology, J1007+2115 ($z = 7.515$) is being viewed at cosmic time $t \sim 1.65$ Gyr, about 770 Myr after the EoR began. J1342+0928

($z = 7.54$) is being viewed at ~ 1.64 Gyr, and J0313-1806 ($z = 7.642$) at ~ 1.62 Gyr. According to the Salpeter relation (Eq. 2), they were created at $t \sim 733 - 765$ Myr if their seeds were $\sim 10\ M_\odot$, or $\sim 829 - 849$ Myr if the seeds were instead $\sim 25\ M_\odot$. The redshift range of their formation would therefore have been $18 \gtrsim z \gtrsim 15$, ideally placed just prior to the onset of the EoR, where one would expect the peak in Pop II and III star formation – and their supernova deaths – to have occurred.

But the timeline disparity between ΛCDM and the early quasars could not be greater than that exhibited by UHZ-1. Detailed studies [42,43], including the state-of-the-art Renaissance simulation suite [44], have shown that the kind of greatly super-Eddington accretion required to produce an object like UHZ-1 in only ~ 300 Myr is probably infeasible given the spatial location of the Pop III supernova seeds.

In $R_h = ct$, we are viewing UHZ-1 at cosmic time $t \sim 1242$ Myr. According to the Salpeter equation, it would have taken this object ~ 750 Myr to grow from a $10\ M_\odot$ seed, or ~ 580 Myr from $25\ M_\odot$. The implied range of redshifts for its birth is thus $27 \gtrsim z \gtrsim 20$, as one may see in Fig. 1. Like the other three high-z quasars shown in this figure, its origin and growth are thus consistent with our current understanding of Pop III star formation and the subsequent accretion these objects would have experienced during their lifetime up to the point at which we detect them.

We must also stress that the $\sim 580 - 750$ Myr required for UHZ-1 to grow via Eddington-limited accretion from its initial Pop III supernova seed at $z \gtrsim 20$ coincides beautifully with two critically important observations. First it was created not long before the onset of the EoR, which is believed to have been sustained by UV photons emitted by the first stars and the black holes they spawned. Second, there is no evidence that it is accreting at a super-Eddington rate. The latter is commonly observed in all the high-z quasars, arguing against anomalously rapid growth as the reason for their appearance much earlier than expected in the standard model.

Of course, it may be too early to claim that the timeline required by the 'too-early' appearance of supermassive black holes is uniquely a feature of just $R_h = ct$. Other possibilities exist for stretching the time versus redshift relation predicted by the standard model. For example, if for some reason Ω_m were to be 0.1 instead of the value 0.307 optimized by *Planck*, then $t(z = 10) \sim 0.8$ Gyrs in ΛCDM, which would be consistent with the features of black-hole growth we have described in this *Letter*. Alternatively, one might contemplate the presence of dynamical dark energy instead of a cosmological constant [45], which could also impact the timeline in the early Universe. It should be mentioned, however, that adjusting the timeline cannot be done independently of all the other observational constraints. In the case of $R_h = ct$, this timeline is built in from the beginning and is consistent with all the ~ 30 comparative tests completed thus far [3]. It would be more challenging to ensure that modifications such as $\Omega_m \to 0.1$ would retain global consistency of the standard model with all of the data available today.

In a very different scenario, the seeds for supermassive black-hole growth might have been primordial black holes, possibly formed around the electroweak, quantum chromodynamics and electron-positron annihilation epochs (see, e.g., Ref. [46] for an excellent review and a much more complete set of references). This possibility would have circumvented the delay in Pop II and III star formation, allowing the seeds to form well before decoupling at $\sim 380{,}000$ years. Even so, however, it is difficult to see how this approach could have reduced the growth time shown in Fig. 2, which stretches the birth event to well before the Big Bang.

4 Conclusion

In this *Letter*, we have highlighted the cosmic timeline implied by the most recently discovered high-z quasars. The reality, however, is that a severe time compression problem with the standard model is suggested by several diverse kinds of source, not just the very early appearance of supermassive black holes. The so-called impossibly early galaxy problem, first identified with the *Hubble Space Telescope* [47,48], has been greatly exacerbated by other recent *James Webb Space Telescope* discoveries of galaxies with spectroscopically confirmed redshifts up to $z \sim 14.32$ and several others with (less reliable) photometric redshifts up to $z \sim 16 - 17$ [49–51]. The most distant confirmed galaxies include JADES-GS-z14-0 ($z = 14.32$) and JADES-GS-z14-1 ($z = 13.90$) [52] and JADES-GS-z13-0 ($z = 13.2$) [53]. In the context of ΛCDM, the ages at which these galaxies appeared fully formed are thus $t \sim 277$ Myr at $z \sim 14$ and ~ 217 Myr at $z \sim 17$.

In the context of the standard model, these $\sim 10^9\ M_\odot$ structures would have had to form just at the time when the first Population III stars were being assembled. But this situation is just as infeasible as the early formation and growth of black holes that we have discussed in this *Letter*. These two major problems with the standard model are, of course, closely related. The astrophysical principles behind the emergence of both classes of source are well understood, and very little, if any, room remains for the adjustments required to mitigate this tension.

The common thread that underlies both anomalies is the apparently incorrect time versus redshift relation predicted by ΛCDM. Not surprisingly, the impossibly early galaxy problem is mitigated by adopting $R_h = ct$ as the background cosmology [54]. These results have significant implications because they rely on a period in the Universe's expansion ($t \lesssim 2$ Gyr) when these two models differ the most. It thus appears that all of the major issues associated with the formation of structure in the early Universe are resolved by the inclusion into ΛCDM of the zero active mass condition, $\rho + 3p = 0$, which would turn it into $R_{\rm h} = ct$ [3].

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